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Observations of Multiple Young-of-the-Year to Juvenile White Sharks (*Carcharodon carcharias*) within South-West Australian Waters and Its Implications for a Potential Nursery Area(s)

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Abstract: The white shark (*Carcharodon carcharias*) is a globally distributed top predator. Due to its ecological importance, increasing knowledge through continued research can enhance management measures. One such facet of biological knowledge is the identification of shark nursery areas, as protection of these regions is critical to species survival. Presently, there are two known *C. carcharias* nursery areas in association with the Eastern Australian subpopulation; however, a nursery area associated with the Southern-Western Australian *C. carcharias* subpopulation has yet to be identified. Herein, we report opportunistic laser photogrammetry, stereo-photogrammetry, and baited remote underwater video systems (BRUVS) data that resulted in the identification of sixteen young-of-the-year (YOY)-juvenile *C. carcharias* from two separate regions (i.e., Salisbury Island and Daw Island) in South-West Australia. Additionally, anecdotal bycatch data associated with two YOY *C. carcharias* (i.e., 1.40 and 1.70 m total length) from another location within the Great Australian Bight are reported. While it is premature to conclude that these sites represent discrete or an expansive interconnected nursery area, the sightings success in this study is indicative that future research may want to consider implementing a study during a similar time period (i.e., February–March) while using a similar attractant methodology (i.e., bottom-set BRUVS baited with squid [*Sepioteuthis australis*]) to help elucidate the unique life-history characteristics of this *C. carcharias* subpopulation.

Keywords: white shark; *Carcharodon carcharias*; shark nursery area; South-West Australia; BRUVS

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1. Introduction

Due to their substantial geographic ranges, considerable challenges exist in obtaining shark ecological data. Furthermore, understanding if a region qualifies as a shark nursery based on the criteria proposed by Heupel et al. (2007) is of upmost importance on both species and ecosystem levels. Presently, there are three commonly accepted criteria that a region must meet to be successfully designated as a shark nursery area: (1) young-of-the-year (YOY) or juveniles are encountered more frequently in the area than in other areas, (2) YOY/juveniles remain in or return to the area over an extended period of time, and (3) there is repeated use of the area over several years by YOY/juvenile sharks [1]. Research on shark nursery areas has increased [2–5] and demonstrates how several biological and environmental variables may not only influence the distribution of the respective species, but also how these shifts in distribution may negatively impact species survival [5]. Furthermore, research demonstrates that all stages of a species' life cycle are relevant [6,7], rather than just the stages that may be inherently more vulnerable to exploitation. Therefore, an increased understanding of shark nursery areas may improve future shark management initiatives to maximize species survival [7,8].

More specifically and due to the fact that adult white sharks (*Carcharodon carcharias*) are characterized by expansive movement patterns [9], the identification of *C. carcharias* nursery areas are of particular interest and conservation importance [2,10,11]. More specifically, YOY/juveniles typically inhabit discrete inshore nursery areas [10,12], enabling more effective location-based management practices (e.g., in United States Territorial Waters) [13]. *Carcharodon carcharias* has a global distribution in both temperate and subtropical seas, and occasionally utilizes tropical waters [11,14–16]. This species is characterized by having low fecundity, producing an average of 2–14 pups per litter [17,18], slow growth [19,20], and late sexual maturity, which is estimated to be >360 cm total length (TL) for males and >480 cm TL for females [10]. Due to its low rebound potential and current estimated stock status, *C. carcharias* is listed as Vulnerable [21] according to the IUCN (International Union for the Conservation of Nature) Red List. Additionally, *C. carcharias* was listed in the CITES (Convention of the International Trade in Endangered Species of Wild Flora and Fauna) Appendix II in 2005 to prevent utilization/exploitation that is incompatible with their survival. However, although protected, this species is captured as bycatch in a variety of fisheries or targeted in several shark control programs [22–24]. Therefore, understanding the movement patterns, habitat preferences, and other ecological and biological characteristics (e.g., identification of nursery area (s)) is essential for all life stages to understand and implement more effective management practices.

Presently, there are two known *C. carcharias* subpopulations in Australia: (1) the Eastern Australian subpopulation [25,26] and (2) the Southern-Western Australian subpopulation [9]. In relation to the Eastern Australian subpopulation, two *C. carcharias* nursery areas have been identified (i.e., Corner Inlet and Port Stephens) [10,11]. However, although research has been conducted in relation to the Southern-Western Australian *C. carcharias* subpopulation [9,16], insufficient data have been provided that confirms the discrete location(s) of a *C. carcharias* nursery area [27,28]. More specifically, Bruce (2016) suggested that the nursery areas associated with this subpopulation may not be discrete but rather extend over broad regions within the continental shelf. Given the lack of data in relation to the potential nursery areas associated with the Southern-Western Australian *C. carcharias* subpopulation and to aid in the biological understanding of this species, the present study describes the opportunistic data collected through various sources (e.g., BRUVS, stereo- and laser-photogrammetry, and anecdotal commercial fishing data) from two different regions (a) the Recherche Archipelago, Western Australia, and (b) a commercial fishing site near Cocklebiddy (Figure 1), Western Australia, to help identify two high priority regions that may represent discrete nursery areas or parts of a broad and interconnected nursery as suggested by Bruce (2016).

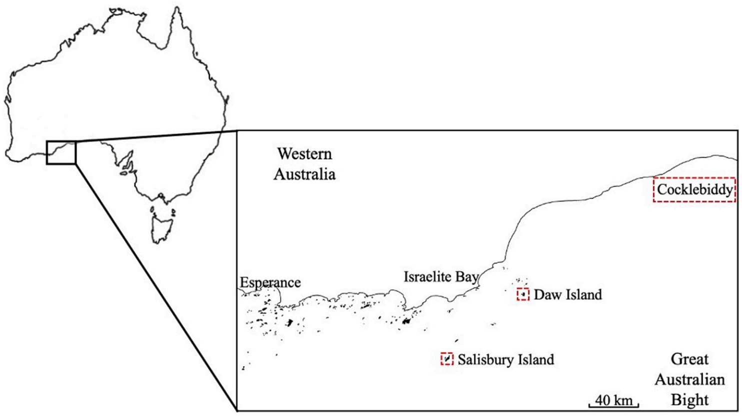

Figure 1. Maps illustrating the study sites. Bycatch data from a commercial gillnet fisherman targeting gummy sharks (*Mustelus antarcticus*) were collected from a site near Cocklebiddy, Western Australia

(32°16′ S, 126°17′ E). This site is characterized by having a sandy seafloor and low visibility conditions. Opportunistic video sampling was conducted in Recherche Archipelago [Salisbury Island (34°21′ S, 123°32′ E) and Daw Island (33°51′ S, 124°08′ E)]. These sites varied in depth and bathymetric structure—from rocky reefs dominated by golden kelp (*Ecklonia radiata*) to sand flats dominated by various seagrass (e.g., *Posidonia australis*).

2. Materials and Methods

To survey for the presence or absence of *C. carcharias* and as part of both a research and natural history filming expedition, opportunistic video sampling was conducted in two locations within the Recherche Archipelago: Salisbury Island (34°21′ S, 123°32′ E) and Daw Island (33°51′ S, 124°08′ E) (Figure 1).

2.1. Baited Remote Underwater Video Systems (BRUVS)

Two 61.0 cm (length) × 45.7 cm (width) BRUVS were constructed out of 5.1 cm diameter PVC piping and equipped with a forward-facing GoPro Hero 8 HD 1080p camera and two Suptig waterproof lights (white light; wavelength = 5500 k) to permit daytime and nighttime observations. Opposite of the GoPro camera, one 20.3 cm × 10.2 cm × 7.6 cm bait cage was attached and baited with species including, squid (*Sepioteuthis australis*), kingfish (*Seriola lalandi*), or pilchard (*Sardinops sagax*). Various bait types were used to maximize the likelihood of *C. carcharias* attraction [29,30], and the bait type used in association with each BRUVS was noted. For each two-hour deployment, the quantity (2 kg) of bait per BRUVS was standardized. Each BRUVS was secured with a 5.0 m long steel cable to prevent gear loss followed by a 30.0 m long nylon rope that was attached to the vessel to facilitate deployment and retrieval of the technology. BRUVS were lowered to the seafloor directly below the anchored vessel. Deployment was done opportunistically and during both daylight (07h00–18h00) and nighttime hours (18h00–07h00).

Once retrieved, *C. carcharias* quantity and resighting frequency were recorded where possible. Distinctive characteristics (e.g., presence/absence of scars, tags, pigmentation patterns, and dorsal fin notch characteristics) were used to identify individual *C. carcharias* [31,32].

2.2. Laser and Stereo-Photogrammetry

To implement both laser and stereo-photogrammetry, a BlueROV2 (Blue Robotics; Torrance, CA, USA) was used. This underwater remotely operated vehicle (ROV) contains a live-feed underwater video transmission, is highly stable (equipped with six, t200 thrusters), and contains high intensity lights to permit both day and night observations. This ROV was deployed opportunistically at both islands to search for *C. carcharias*. However, only at Salisbury Island in February 2020, the ROV was equipped with multiple pre-calibrated cameras (i.e., calibrated using a 3D calibration cube) to facilitate stereo-photogrammetry to measure any interacting organisms. Stereo-photogrammetry estimates the three-dimensional coordinates of points on an object (e.g., a shark) using measurements made in the two screen captures (i.e., still images) obtained from the video associated with the strategically placed GoPro Hero 8 HD 1080p cameras [33,34]. To estimate shark total length, the online program VidSync (Version 1.661, University of Alaska Fairbanks, Fairbanks, AK, USA) was used.

Furthermore, and to implement the laser photogrammetry technique at both Salisbury and Daw Island in February 2021, the ROV was equipped with high powered 20 mW green parallel lasers (Marine Design Engineering Ltd.; Auckland, New Zealand; www.marinedesign.co.nz). The lasers were pre-calibrated to 0.33 m to ensure technique accuracy. As implemented in previous studies, lasers were properly positioned onto the side of the focal animal by maneuvering the ROV and post-hoc image analysis was implemented to obtain shark total length (TL) estimates (see Figure 2) [35,36]. Using these TL estimates, sharks were then categorized as YOY (i.e., <1.75 m TL), juveniles (i.e., 1.75–3.79 and 1.75–4.5 m TL for males and females, respectively), or mature adults (i.e., >3.79 and >4.5 m TL for males and females, respectively [10,17,19,37]).

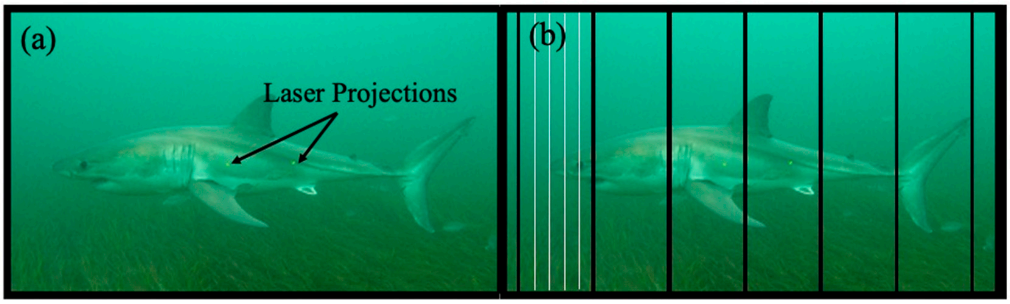

Figure 2. Laser photogrammetry image captured by the laser-equipped Blue Robotics Underwater remote operated vehicle (BlueROV2) of an early-stage juvenile white shark (*Carcharodon carcharias*) at Daw Island in March 2021. (**a**) The parallel laser projections can be seen on the flank of the shark. (**b**) This image was then rescaled to fit a measurement template (i.e., black vertical lines with each space representing 0.33 m and white vertical lines representing 6.6 cm) allowing the determination of this shark's total length of 1.85 m.

3. Results

Over the span of 13 days during February and March 2020–2021, the technologies were opportunistically deployed at both sites within the Recherche Archipelago to assess *C. carcharias* presence or absence. Throughout the expeditions, sea surface temperature ranged from 18.0 to 20.5 °C and water depth ranged from 13.0 to 17.0 m at Salisbury Island and 20 to 22 °C and 9.0 to 13.0 m at Daw Island.

3.1. Stereo-Photogrammetry

On one occasion, stereo-photogrammetry was implemented at Salisbury Island on an interacting *C. carcharias*. Based on VidSync stereo-photogrammetry analysis, this male shark was estimated to have a total length of 1.58 m and was categorized as a young-of-the-year (YOY) shark (Table 1).

3.2. Laser Photogrammetry

During the first year (2020; n = 5 days) at Salisbury Island, a total of six different *C. carcharias* were successfully identified and measured using laser photogrammetry. All sharks were male and ranged in TL from 2.8 to 3.9 m (mean ± S.D.; 3.43 m ± 0.39; Table 1). More specifically, six juveniles (2.8–3.7 m TL) and one adult (3.9 m TL) were identified.

Data were collected over the span of eight days from two locations during the 2021 expedition. At Salisbury Island (n = 5 days), a total of five different *C. carcharias* were successfully identified and measured. These sharks were male and ranged in TL from 2.7 to 3.7 m (3.24 m ± 0.37; Table 1). Of these sharks, all were considered juveniles (2.7–3.4 m TL). At Daw Island (n = 3 days), five sharks were identified and successfully measured. Two of these sharks were identified as male, one as female, and two were unidentified. Sharks ranged in TL from 1.7 to 2.2 m (1.94 m ± 0.19; Table 1), with one being categorized as a YOY shark (1.7 m TL) and the remaining four being categorized as juveniles (1.8–2.2 m TL).

3.3. BRUVS: Salisbury Island

Over the course of ten days and during both expeditions (i.e., 2020–2021), approximately 22 h of BRUVS footage was collected. From this footage, multiple sharks (n = 11) were identified. The sharks were previously encountered when implementing laser and stereo-photogrammetry and therefore size ranged from 2.7 to 3.9 m (3.35 m ± 0.38). Of these eleven sharks, five returned to the site on at least one subsequent day. Three sharks were observed to remain at the site for at least two days, and one juvenile shark (2.7 m TL) was observed on four consecutive days (Expedition 2: 2021).

Table 1. Total length (TL) measurements collected from white sharks (*Carcharodon carcharias*) encountered at Daw Island, Salisbury Island, and Cocklebiddy, Western Australia. These TL measurements were collected using laser and stereo-photogrammetry as well as from bycatch associated with the bottom gillnet fishery targeting gummy sharks (*Mustelus antarcticus*). Sex is denoted as male (M), female (F), or unknown (UNK). Mature adult sharks are identified by bold and italicized text (n = 1), whereas young-of-the-year and juvenile sharks are identified by normal text (n = 18).

Location	Date	Total Length (m)	Sex
Salisbury Island	February 2020	1.6	M
		2.8	M
		3.9	***M***
		3.4	M
		3.6	M
		3.7	M
		3.2	M
	March 2021	3.4	M
		3.7	M
		2.7	M
		3.3	M
		3.1	M
Daw Island	March 2021	1.7	M
		1.8	M
		2.0	F
		2.0	UNK
		2.2	UNK
Cocklebiddy	2018	1.4	F
	2019	1.7	F

3.4. BRUVS: Daw Island

Over the course of three days in 2021, a total of 12 h of BRUVS footage was collected. Three different sharks were identified from this location. When paired with the images associated with the laser photogrammetry results, all three of these sharks were successfully measured (1.7 m, 1.8 m, and 2.0 m TL). These sharks appeared on the BRUVS on all three days of deployment (Figure 3).

Figure 3. Examples of young-of-the-year (YOY) and juvenile white shark (*Carcharodon carcharias*) interactions on the baited remote underwater video systems (BRUVS; **a**–**e**) and the BlueROV2 (**c**,**f**). These images were captured at Daw Island, Western Australia—33°51′ S, 124°08′ E.

4. Discussion

This study provides empirical evidence of sixteen YOY-juvenile *C. carcharias* utilizing two geographically close regions within South-West Australia over a short temporal scale (i.e., 12.5 days across 2 years). Specifically, several young-of-the-year (YOY) and juvenile *C. carcharias* were successfully identified, with multi-day site fidelity (i.e., three days and four days) being observed at the Daw Island and Salisbury Island sites, respectively. Beyond the opportunistic sampling implemented in the present study, two anonymous fishermen provided broad and anecdotal sightings reports from 2018 to 2020 from Cocklebiddy, Western Australia (Figure 1), a region that is geographically close (329.0 km) to both Daw and Salisbury Islands. Sightings of small sharks (<2.0 m) were numerous (i.e., multiple YOY-juvenile sharks per trip) and were observed throughout the year. Although YOY-juvenile shark quantity cannot be computed based on the provided sightings reports, the data associated with two *C. carcharias* captures were provided (Figure 4). These sharks were 1.40 m and 1.70 m in total length, had no presence of scars, both were female, and captured in June 2020 and November 2020, respectively. Therefore, in combination with the opportunistic data collected in the present study, the associated sightings reports and bycatch data provided by the commercial fishermen suggests that these sites may be of importance to the Southern-Western Australia *C. carcharias* subpopulation and warrants further investigation.

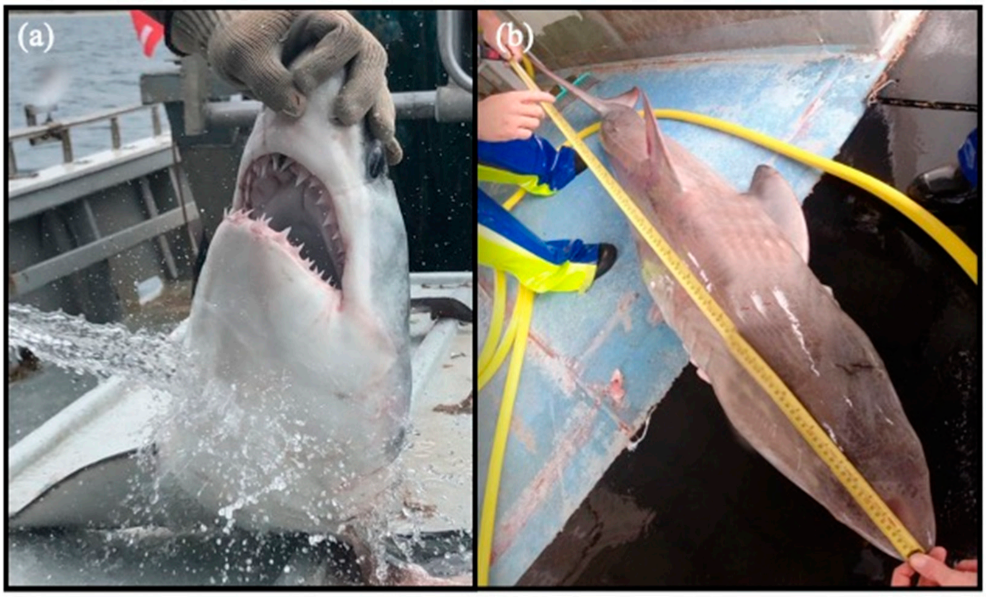

Figure 4. Examples of white shark (*Carcharodon carcharias*) bycatch associated with a commercial fishery operation at a site near Cocklebiddy, Western Australia; 32°16′ S, 126°17′ E). (**a**) A 1.40 m total length (TL) *C. carcharias* female captured in 2020. (**b**) A 1.70 m TL *C. carcharias* female captured in 2020.

Presently, the identification of discrete nursery area(s) habitat associated with the Southern-Western Australian *C. carcharias* subpopulation has yet to occur. While the opportunistically collected data reported in the present study can contribute to the overall growing body of knowledge pertaining to the *C. carcharias* nursery area(s) associated with this subpopulation, it is important to note that a more rigorous field study is warranted to determine if these regions fulfill the three shark nursery area criteria proposed by Heupel et al. (2007). For the two sites with the Recherche Archipelago (i.e., Salisbury and Daw Islands), the data fulfill one nursery area criteria. More specifically, there is repeated use of the area over several years by YOY/juvenile sharks as evidenced by YOY sharks being identified using stereo-photogrammetry in 2020, through laser photogrammetry and BRUVS in 2021 (i.e., YOY sharks identified in this region in 2020 and 2021), and anecdotal observations of YOY-juvenile sharks in 2015 and 2019 (Payne, Pers. Comm.). Some may argue that the data may marginally fulfill a second criteria, since YOY and juvenile sharks remained in the region for up to four days as evidenced with BRUVS deployed at Daw Island in 2021 (i.e., three sharks were reidentified at the site over three consecutive days) and Salisbury Island in 2021 (i.e., one shark was reidentified at the site for four consecutive days). However, the presence of olfactory and gustatory cues (e.g., chum) may have temporally influenced the natural presence of these sharks and thus site fidelity cannot be accurately determined and consequently casts doubt on the fulfillment of a second nursery area criteria. Due to this, it is recommended that more substantial, detailed, and localized habitat use data are collected as evidenced in many ultrasonic [38] and satellite tagging studies [10] to determine the extent of YOY-juvenile *C. carcharias* residency associated with both regions. Furthermore, beyond the catch data provided by the commercial fishermen, sightings data were insufficient and lacked detail in relation to the Cocklebiddy region. Therefore, data from this region did not fulfill any of Heupel et al. (2007) nursery area criteria; however, due to the multi-year sightings frequency and notable captures, this area may also represent an important region for the Southern-Western *C. carcharias* subpopulation and should be investigated further.

Beyond future research identifying if these previously described regions within the Great Australian Bight represent a nursery area(s), additional questions arise as to whether these regions may represent one interconnected nursery area where sharks utilize specific sites on a seasonal basis or discrete nursery areas. For instance, *C. carcharias* nursery areas have been demonstrated to be expansive [11,39]. The Port Stephens, New South Wales, *C. carcharias* nursery area ranges approximately across 160.0 km and similarly, the Western North Atlantic Ocean *C. carcharias* nursery area is estimated to exist within the New York Bight [4,40], spanning approximately 400.0 km of shoreline. In the present study, the three sites (i.e., Salisbury Island, Daw Island, and the Cocklebiddy region) were located in various regions within the Great Australian Bight. The maximum straight-line distance between these sites was 329.0 km (i.e., Cocklebiddy to Salisbury Island). Therefore, should this region be characterized as a *C. carcharias* nursery area, it is possible that it may be one interconnected and expansive nursery habitat as previously suggested by Bruce (2016) and as evidenced with habitat use by YOY-juvenile *C. carcharias* within other previously described nursery areas [11,41]. In addition, previous efforts in January–February 2017 within this region have produced late-stage juvenile *C. carcharias* that ranged approximately from 2.5 to 3.5 m [28], similar to what was encountered at Salisbury Island in the present study (2.7–3.9 m TL), with the exception of one YOY shark (1.6 m TL). Due to the geographic remoteness of our study sites in combination with logistical difficulties, should future *C. carcharias* nursery area research be implemented, it is recommended that a specific focus be placed on Daw Island, due to the size and quantity of YOY-early-stage juvenile sharks encountered and, if feasible, the Cocklebiddy region to maximize the potential for success at capturing YOY-small juvenile *C. carcharias* within a given experimental time frame. In addition, since previous *C. carcharias* nursery area studies demonstrate that there is a seasonality to YOY-juvenile shark movements [10,11,42] and certain attractant methods (e.g., BRUVS baited with squid [*Sepioteuthis australis*]) yield high neonate-YOY *C. carcharias* sightings [4], it may be important to survey the aforementioned sites (i.e., Daw Island and the Cocklebiddy region) during a similar time period (i.e., February and March) while using similar attractant methods to maximize encounters with YOY-juvenile *C. carcharias.*

5. Conclusions

Due to the low rebound potential of *C. carcharias*, research focusing on specific life stages (e.g., young-of-the-year and juvenile) and essential habitats (e.g., nursery areas) is critical for proper protection and management of the species. Considerable effort has been implemented to identify these nursery areas since the protection of these regions may contribute to population stability and recovery. Therefore, the present study provides insight into both location- and methodological-based approaches that may maximize YOY-early-stage juvenile *C. carcharias* attraction for future studies in association with the Southern-Western *C. carcharias* subpopulation. However, while the present methodology may be suitable for YOY-early-stage juvenile *C. carcharias* attraction, the present technological approach may be insufficient and impractical to accurately assess the distribution and residency patterns of these YOY-juvenile sharks within this region. Therefore, it is recommended that future studies implement tagging methodologies (e.g., acoustic and satellite tags) in combination with the attractant methodologies implemented and seasonality in the present study to comprehensively analyze the multi-year fine- and broad-scale movements of these sharks.

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Conflicts of Interest: The authors declare that they have no conflict of interest.

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